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Design and manufacture of oscillatory propulsion robot fish

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The objective of this study is to design an oscillatory propulsion robot fish by observation and divide it into two systems, namely, mechanism and control systems. Mechanism system includes the mode of movement and stability. Movement parameters of linkage are determined by numerical simulation, gravity and the buoyancy of a stability design can reduce the change center of gravity instrument and cost. Control system comprises a controller, an actuation circuit, a sensing circuit, and a waterproof sealing. Finally, the robot fish is finished through the realizability of manufacturing, functional evaluations, experiments, and tests.

[**Keywords:** Robot Fish, Oscillatory Propulsion, Mechanism System, Control System]

Introduction

Movement of fish has the features of high efficiency, low energy consumption and maneuverability. Hence, a robot fish has been a primary study area in marine engineering.

Robotic fish is designed to swim in water, Further, as a functional requirement, it must resemble a real fish in appearance. It should have a life-like interaction with the environment[1]. Past studies have categorized robotic fish according their swimming function and body form. Type of swimming is categorized into undulatory motion and oscillatory motion. When classified by oscillating parts, robotic fish can be sorted into fish with body and/or caudal fins (BCF) or fish with median and/or pair fins (MPF). Body forms are also different with regard to the difference in oscillation, such as eels' anguilliform mode and whales' thunniform mode. The robot fish must be designed on the basis of the mode of swimming and body form[2,3].

With regard to the propulsion and body oscillation of robot fish, large and medium-sized fish can be designed using a conventional method, the design method is a ***N***-joint oscillating mechanism that supplies cruise straight, c-shape and s-shape movement[4,5]. Because of the difficulty of the assembly mechanisms for small fish, shape-memory alloy or polymeric artificial muscles can be used in order to attain the effect of propulsion by controlling the oscillating mechanism with electric current[6,7].

Present study is an attempt to understand the mode of movement of fish by analyzing and simulating the movement mechanism of robot fish and carrying out tail oscillation through the integrated design of the mechanism, circuit control, and chip.

Design process planning

In robot fish design, we intend to build the physical model and the analytical method through observation, develop the mechanism and the movement mode for the robot fish to reduce errors in manufacturing, conduct an experiment, and finally test the robot fish underwater. The entire design of the robot fish is illustrated in Fig. 1, including the design and parameters gathered through observation, the movement mode of the mechanism system, and the stability and numerical simulation; the control system that includes the controller, actuation circuit, sensing circuit, and watertight sealing; and the manufacturing realizability and evaluation of the functional requirements at the last stage.

Materials and Methods

Observation of nature

In the first step of robot fish design, we observe the movement mode of fish and classify these movements into "advancing, turning, floating, or diving" to build

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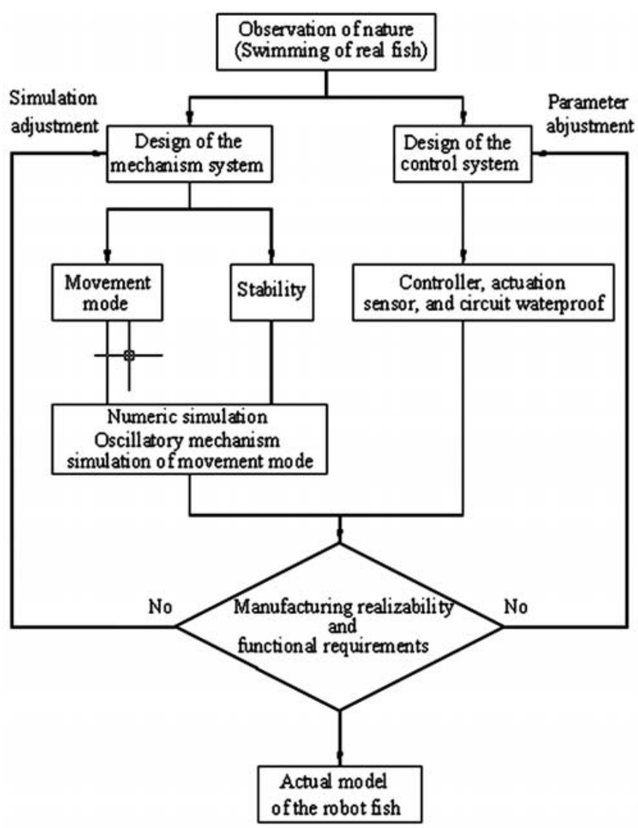

Fig. 1—Design Flowchar

the undulation equation for the movement path on the basis of the body oscillation. In order to carry out the movement mode of oscillation, the robot fish system is classified into mechanism design and control system, therefore, we would investigate mechanism design and control system in the next section.

Design of the mechanism system

Fish swim extremely smooth in water. It is a great challenge to design a mechanism that enables robot fish to swim like real fish and yet have the functionality and realizability of a robot fish. The aim of a robot fish design is to attain the functional requirements of fish, namely, advancing, turning, floating, and diving. Mechanical structure will be quite different from that of the fish itself. In light of the functional requirements, we further classify the design of a robot fish's mechanism system into movement mode and stability.

The movement mode of fish combines several joints and pulls tendons to deliver the function of movement. Oscillating modules are built by the mechanism and actuators to carry out the movement function of a robot fish. Modules are combined into the oscillating mechanism, which enables a robot fish to swim like real fish. The movement mode can be categorized into "oscillating the tail while moving forward, turning during movement, floating, and diving by oscillation of the pectoral fin."

A robot fish's stability in water influences its posture and balance in water. Stability can be classified into dynamic and static. Dynamic stability refers to the stability of robot fish under the inertia of momentum while moving. Static stability refers to the stability when a robot fish does not move and its inertia of momentum is zero. The balance weight is closely related to buoyancy. It is the technique to achieve stability, control, and the reserved buoy. In this study, the robot fish's buoyancy is controlled by hanging buoy boxes to ensure that its balance weight approaches the water density. This enables the robot fish to remain still in the water and not overturn because of the water current or its oscillation.

Design of the control system

If the mechanism is the body of a robot fish, the control system is the robot fish's brain; this system carries out the function of turning, advancing, or avoiding obstacles through input/output signals. A robot fish's control system can be classified into the controller, actuation circuit, sensing circuit, and watertight sealing. Control center is mainly a microchip responsible for calculating the position and speed of the oscillating mechanism and the position of obstacles and for carrying out avoidance strategies like the human brain does. Designer of the actuation circuit should first decide on its specifications, such as the angle, position and speed of oscillation; magnitude of torsion; and control signals of the actuation circuit. Designer of the sensing circuit should consider the type of power provided by the entire system and the direction and distance of sensing. To ensure non-contact or reflective sensors should be selected. After considering the price and circuits of the sensing assembly, we select an infrared sensor to detect and avoid obstacles.

Numerical simulation

Creating a robot fish is a challenging task. We hope to forecast manufacturing and design problems through numerical simulations. When applied to a robot fish's mechanism, these simulations can provide the length of each link in the oscillatory mechanism and the angle, speed and time sequence of the oscillation so that the mechanism system can complete the actions of advancing and sharp turning. On the basis of the information on the mechanism system, the control system plans the position of the actuator, speed control, the radius of sharp turning, the sensor's valid distance of sensing and the time of response. They are then simulated and analyzed through the time sequence of the actuation in order to considerably reduce the errors in design and manufacturing.

The fish's body slants when advancing or turning through oscillation. A designer can forecast the angle of inclination and possibility of overturning through a numerical simulation and provide further parameters for adjusting the extent of oscillation and the turning angle to make the robot fish swim more smoothly.

Manufacturing realizability and functional requirements

With regard to the functional requirement for a robot fish to simulate the swimming effect, the designer of the mechanism or control system will be informed of the problems identified during manufacturing. Common problems related to the mechanism include dimension, manufacturing, and assembly of link elements and oscillation tests without the electric control system. Common problems related to the control system include the manufacturing of the controller and sensing circuit, detection of the sensing distance, control of the oscillating position and the speed of actuator, and the final action test. If a robot fish does not satisfy the design requirements, the design of the mechanism and control systems are revised in order to ultimately deliver a robot fish with functions such as advancing, avoiding obstacles, floating, and diving.

Movement analysis of robot fish

Observation of nature

This paper aims to develop a biomimetic fish that can be used in water, the motion information of the real fish is important, by the observation, to simulate the movement of real fish, fish action was captured on camera, and the real fish's advancing and turning actions were resolved for the analysis of movement parameters and numerical simulation.

Fig. 2 show the advancing and turning frames of the fish, respectively. In the "advancing" frame, the oscillatory propulsion is symmetrical. From the action resolution of the half-cycle oscillation, we find that "at the moment when the fish begins to move, it pushes the water to produce eddy currents, and its body oscillates like the letter S. The fish then pushes through the fluid flow and accelerates." In the "turning" frame, the fish stays still at first and then begins to move. It stirs the water and then turns by twisting its body. In designing the fitting mechanism, three links are used to match the action of a real fish, the black line and node are expressed link and joint, respectively.

Link movement analysis

The spinal curve when the fish oscillates through body and tail propulsion can be described by the undulation equation expressed below as[8,9,10]

$$y_{body}(x,t) = (c_1 x + c_2 x^2)\sin(kx + \quad t) \qquad \dots (1)$$

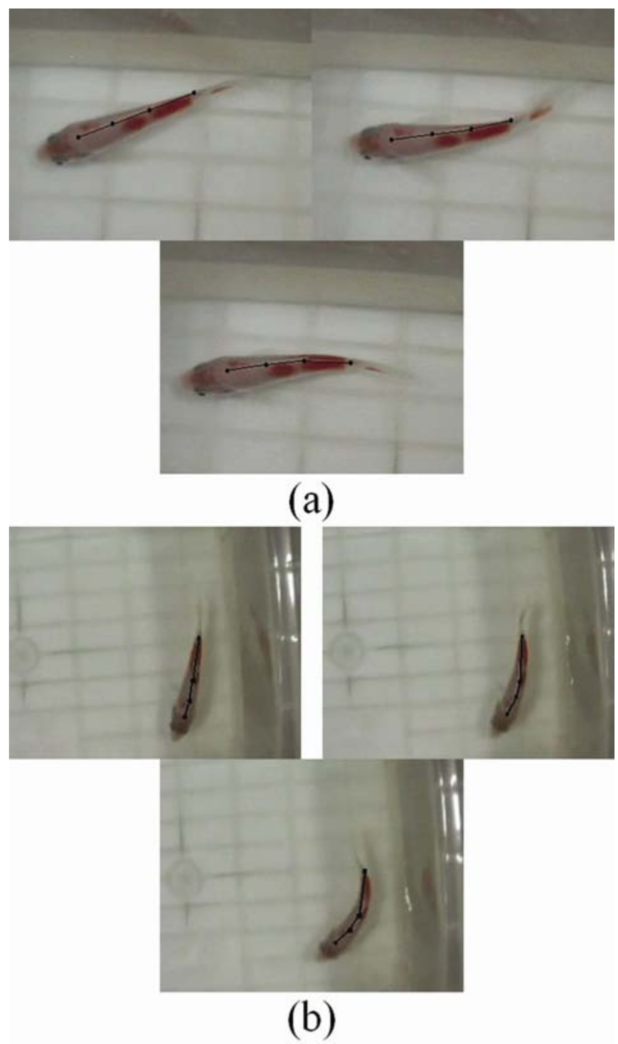

Fig. 2—(a) Advancing Action (b) Turning Action

In Eq. (1), $\boldsymbol{y}_{body}$, x, t, k, , c_1, and c_2 are a fish body's transverse displacement, longitudinal coordinates along with the main axis, time, wavelength constant for fish oscillation, wave frequency, linear gain of the amplitude envelope and the quadratic wave amplitude envelope, respectively.

If the wavelength multipliers of the fish oscillation $\omega=\frac{2}{\boldsymbol{T}}$ and $k=\frac{2}{\ }$ are substituted into the equation, Eq. (1) can be rewritten as:

$$\boldsymbol{y}_{body}(\boldsymbol{x},\boldsymbol{t}) = (\boldsymbol{c}_1\boldsymbol{x}+\boldsymbol{c}_2\boldsymbol{x}^2)\sin(\frac{2\ \boldsymbol{t}}{\boldsymbol{T}}+\frac{2\ \boldsymbol{x}}{\ }) \quad \ldots (2)$$

In Eq. (2), λ and T are the wavelength and period, respectively, of oscillation.

The robot fish mechanism has multiple links, as shown in Fig. 3. The coordinates of the end node of link n is $P_n(x_n,y_n)$, and its geometric relationship is illustrated as follows:

$$\boldsymbol{p}_{x_1} = \boldsymbol{R}_1\cos(\ _1)$$
$$\boldsymbol{p}_{y_1} = \boldsymbol{R}_1\sin(\ _1) \quad \ldots (3.1)$$

$$\boldsymbol{p}_{x_2} = \boldsymbol{R}_1\cos(\ _1)+\boldsymbol{R}_2\cos(\ _2)$$
$$\boldsymbol{p}_{y_2} = \boldsymbol{R}_1\sin(\ _1)+\boldsymbol{R}_2\sin(\ _2) \quad \ldots (3.2)$$

$$\vdots$$

$$\boldsymbol{p}_{x_n} = \boldsymbol{R}_1\cos(\ _1)+\boldsymbol{R}_2\cos(\ _2)+\cdots+\boldsymbol{R}_n\cos(\ _n)$$
$$\boldsymbol{p}_{y_n} = \boldsymbol{R}_1\sin(\ _1)+\boldsymbol{R}_2\sin(\ _2)+\cdots+\boldsymbol{R}_n\sin(\ _n) \quad \ldots (3.3)$$

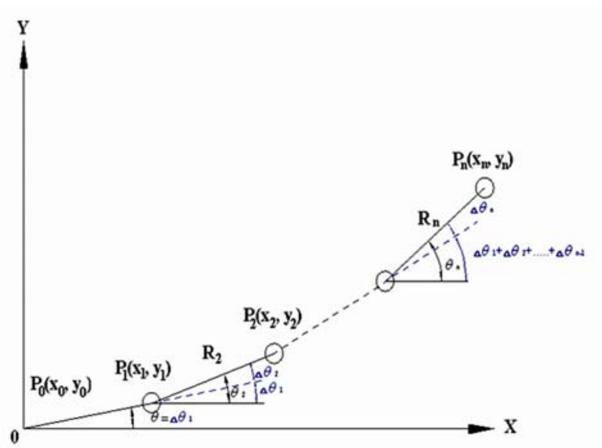

Fig. 3—Multilink Node Coordinates

Eqs. (3.1) to (3.3) are generalized as

$$\boldsymbol{P}_{x_n} = \sum_{i=1}^{n-1}\boldsymbol{R}_i\cos\ _i \quad \ldots (4.1)$$

$$\boldsymbol{P}_{y_n} = \sum_{i=1}^{n-1}\boldsymbol{R}_i\sin\ _i \quad \ldots (4.2)$$

The angular geometric relationship for link oscillation is expressed as follows:

$$_1 = \Delta\ _1 \quad \ldots (5.1)$$
$$_2 = \Delta\ _1 + \Delta\ _2 \quad \ldots (5.2)$$
$$\vdots$$
$$_n = \Delta\ _1 + \Delta\ _2 + \cdots + \Delta\ _4 \quad \ldots (5.3)$$

Here, $\Delta\ _i$ is the angle of oscillation of the $\boldsymbol{i}^{th}$ link.

Eq. (1) of fish oscillation can provide information for determining the displacement required in Eq. (4) and the angle required in Eq. (5).

Robot fish stability

The stability of robot fish is defined while the caudal fin's extend of oscillation can'not overturn in the water, also, the center of gravity and the buoyancy of a robot fish are two-importance factor in the stability. While the robot fish swings its caudal fin to cause a torque of inclination, also, the center of gravity and the buoyancy must produce a right moment to keep the stability of robot fish, if we properly use the center of gravity and the buoyancy to design robot fish, it would cut down the change center of gravity instrument. In addition to the inertia and momentum of the fish while moving, the stability of a robot fish is difficult to examine while it is swimming. However, the possibility that the robot fish overturns while making a sharp turn after staying still and oscillating its tail can still be explored. The entire weight of a robot fish is distributed when the caudal fin oscillates, as shown in Fig. 4. Fig. 4a shows that the body of the fish is a straight line. Each cross section has a net weight of (the sum of buoyancy and its weight) $\boldsymbol{W_i}$, $\boldsymbol{i}$ = 0, 1, 2, 3, … , $\boldsymbol{n}$, and the equivalent center of gravity and buoyancy are G and B, respectively. Fig. 4b shows the analysis of the entire weight of the fish when the tail oscillates. As the center of gravity deviates from the central axis Z of the fish, it produces a torque of inclination. Its mathematical relationship is given as

$$\boldsymbol{M}_F = \sum_{i=0}^{n}\boldsymbol{W}_i\boldsymbol{X}_i \quad \ldots (6)$$

When the caudal fin oscillates, the equivalent center of gravity G and buoyancy B of the entire fish move to a new position. When the robot fish tilts under the torque of inclination in Eq. (6), the center of gravity G produces the righting moment under the center of buoyancy B, as shown in Fig. 4.c. Therefore, $\boldsymbol{M}_R$ is given as:

$$\boldsymbol{M_R} = \Delta * (\overline{\boldsymbol{BG}}) \sin \quad \ldots (7)$$

while is the buoyancy. To prevent overturning, the torque of inclination $\boldsymbol{M_F}$ is equal to the righting moment $\boldsymbol{M}_R$ when the caudal fin oscillates. In the caudal fin design, its net weight $\boldsymbol{W_n}$ or position $\boldsymbol{X_n}$ should be reduced or lowered as much as possible in order to reduce the torque of inclination $\boldsymbol{M_F}$ If the robot fish's inclination α is reduced, the fish will not overturn.

Through observation, we might find that "when a regular fish swims in water, most of its weight concentrates at the forepart of the body". Fish density is close to that of water. When the fish oscillates its tail to advance or turn, the net weight of each section approaches zero by adjusting the buoy box. The torque of inclination produced is smaller. This will neither cause the fish body to shake much nor influence its overall integrity, which is quite useful in achieving straight routing and stability.

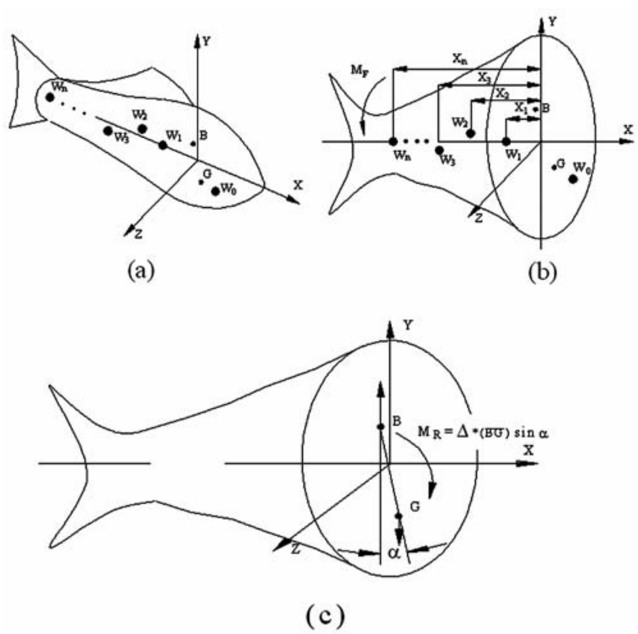

Fig. 4—Weight Distribution When the Tail Oscillates

Numerical simulation

The aim of the numerical simulation is to provide the dimensions for the design of the mechanism system and parameters for the control system. Eq. (1) is the wave function for the simulation of the oscillatory propulsion. The oscillation path of the robot fish can be drawn on the basis of Eq. (1), as shown in Fig. 5. In Fig. 5, the robot fish's body oscillation curve is generated using the parameters in Eq. (1) (range of x: 0~150 mm, each step is 0.1 mm). The curve is used by general fish to push the fluid.

A robot fish's oscillatory mechanism is built by links. The length of each link and angle of oscillation should match the fish curve in the undulation equation. In this study, we use a numerical method to build the angle of oscillation for the oscillatory mechanism and fish curve. The length of each link of the oscillatory mechanism is R_i. The coordinates of the fish curve are (x_i, y_i), the starting position is (x_{si}, y_{si}), and the ending position is (x_{ei}, y_{ei}) of each link. Further, the length between two points should be equal to the length of the link. The function for assessing the minimum error of search is given as:

$$\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}) = \arg\ \min\left[\left(\boldsymbol{R_i} - \sqrt{(\boldsymbol{x_i} - \boldsymbol{x_{si}})^2 + (\boldsymbol{y_i} - \boldsymbol{y_{si}})^2}\right)^2\right] \ldots (8)$$

When the coordinates (x_i, y_i) of the fish curve are substituted into Eq. (8), and the value of $\boldsymbol{f}$ (x, y) is minimum, the coordinates of the curve (x_i, y_i) are the ending point of the $\boldsymbol{i}^{th}$ link, and the angle between the link and horizontal plane can be obtained using the formula

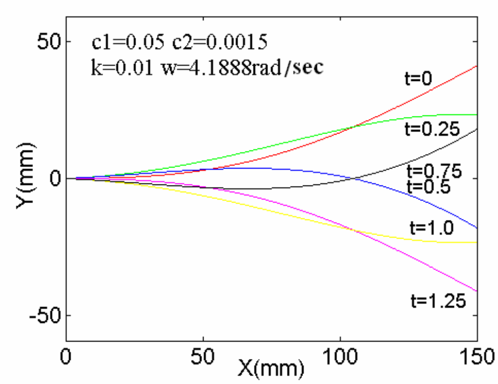

Fig. 5— A Robot Fish's Six Undulation S Curves

Table 1—Oscillation Data of the Links in the Oscillatory Propulsion

	1st Oscillation Curve				2nd Oscillation Curve				3rd Oscillation Curve			
Node	X	Y	θ_i	□θ	X	y	θ_i	□θ	x	y	θ_i	□θ
$P_1(X_1,Y_1)$	49.8	2.96	3.41	3.41	49.5	6.15	7.08	7.08	49.7	3.24	3.73	3.73
$P_2(X_2,Y_2)$	97.9	15.99	9.28	5.87	98.1	17.35	10.03	2.95	99.5	1.03	0.60	-3.13
$P_3(X_3,Y_3)$	142.9	37.39	14.67	5.39	147.6	23.22	8.94	-1.09	146.4	-15.98	-6.23	-6.82
	4th Oscillation Curve				5th Oscillation Curve				6th Oscillation Curve			
Node	x	y	θ_i	□θ	x	y	θ_i	□θ	x	y	θ_i	□θ
$P_1(X_1,Y_1)$	49.8	-2.97	-3.41	-3.41	49.5	-6.15	-7.08	-7.08	49.7	-3.24	-3.73	-3.73
$P_2(X_2,Y_2)$	97.9	-15.99	-9.28	-5.87	98.1	-17.35	-10.03	-2.95	99.5	-1.03	-0.60	3.13
$P_3(X_3,Y_3)$	142.9	-37.39	-14.67	-5.39	147.6	-23.22	-8.94	1.09	146.4	15.98	6.23	6.82

$$_{i} = \tan^{-1}\left(\frac{y_{ei} - y_{si}}{x_{ei} - x_{si}}\right) \quad \ldots (9)$$

The angular increment when each link oscillates can be obtained from Eqs (5) and (9).

To simulate the data of the fish oscillation curve shown in Fig. 5, we change the X value (0~150 mm, each step is 0.1 mm) and match the oscillatory mechanism of the three links. In the matching process, all the links are 50 mm in length. The steps are as follows:

(1) Starting from the first link, make the first point of the fish oscillation curve equal to the starting point of the first link (x_{s1}, y_{s1}). Calculate each point using Eqs. (8) and (9) to obtain the angle between the ending point (x_{e1}, y_{e1}) of the first link and the horizontal plane, $_1$.

(2) Take the ending point of the first link (x_{e1}, y_{e1}) as the starting point of the second link (x_{s2}, y_{s2}).

(3) Repeat steps 1 and 2 to build the 6 fish oscillation curves and the corresponding data of link oscillation.

In the numerical simulation, the oscillatory device of the mechanism system is simulated by three links. Similar to the actual design of the oscillatory mechanism, in this simulation, the angular increment of oscillation of each link can be obtained. Table 1 shows the angle of oscillation when all the links in the oscillatory propulsion mechanism are 50 mm in length. It provides the angle of the oscillating link of each actuator when the robot fish advances by undulation. Fig. 6 presents the fish curve by matching the three links in the oscillatory propulsion.

The links at the two ends of the oscillation are analyzed for the stability of the robot fish when swimming and turning. As the fish density is close

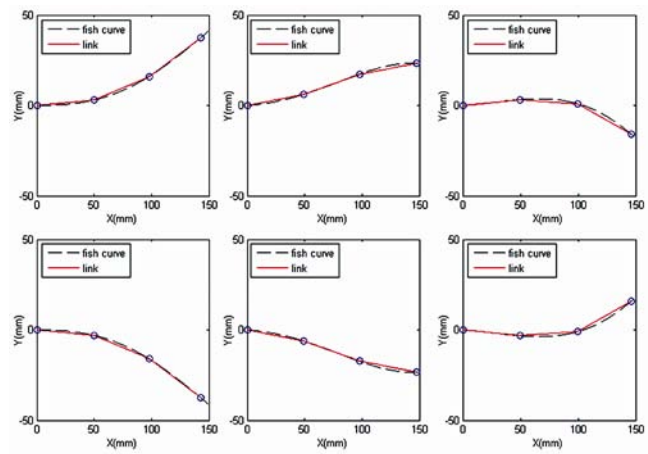

Fig. 6— Fish Curves Obtained by matching the three links

to that of water, the net weight of each section approaches zero and the torque of the inclination produced is considerably less. In the four areas of weight distribution, the net weight of each section is $\boldsymbol{W}_0$ = 1 g, $\boldsymbol{W}_1$ = 1 g, $\boldsymbol{W}_2$ = 2 g, and $\boldsymbol{W}_3$ = 1 g, and the weight distribution position is $\boldsymbol{X}_0$ = 0 cm, $\boldsymbol{X}_1$ = 0 cm, $\boldsymbol{X}_2$ = 2 cm, and $\boldsymbol{X}_3$ = 8 cm, respectively. The distance $\overline{\boldsymbol{GB}}$ between the center of gravity and buoyancy of the entire fish is equal to 2 cm. As calculated by Eq. (6), the torque of inclination is 12 g-cm, and the buoyancy of fish is = 1500 g. Hence, the inclination of fish can be obtained from Eq. (7), α = 0.23°. With this inclination, the fish will not overturn. A fish oscillates to a lesser extent when swimming than when making a turn. Hence, the extent of oscillation should be less than that of turning.

Manufacturing and testing

The manufacturing of robot fish is categorized into oscillatory mechanism, control system and waterproof sealing. In the numerical simulation of the mechanism, the oscillatory device simulates the oscillatory propulsion with three links.

For carrying out the oscillatory mechanism, the oscillatory propulsion is used as the oscillation of the robot fish.

The control system generates the signals directly through double chips to control the servomotor. The waterproof sealing is applied on the servomotor, sensor, and electric circuit. The detailed procedure is given as follows:

Oscillatory mechanism

The angular increment of each link's oscillation is simulated numerically. For example, Table 1 shows the oscillatory angle of 50 mm long links and provides the angle of the oscillatory links of each actuator when the robot fish advances by oscillation. The oscillatory mechanism is designed mainly as a combination of the three actuators. The joint connectors are made of PE for its low weight and convenience in manufacturing. In order to effectively reduce the distance between the oscillating joints and to prevent the mechanism from interfering when the actuator is installed, the turning radius of the slewing axis is minimized, which also ensures smooth oscillation. Fig. 7 illustrates the combination of the oscillatory joints.

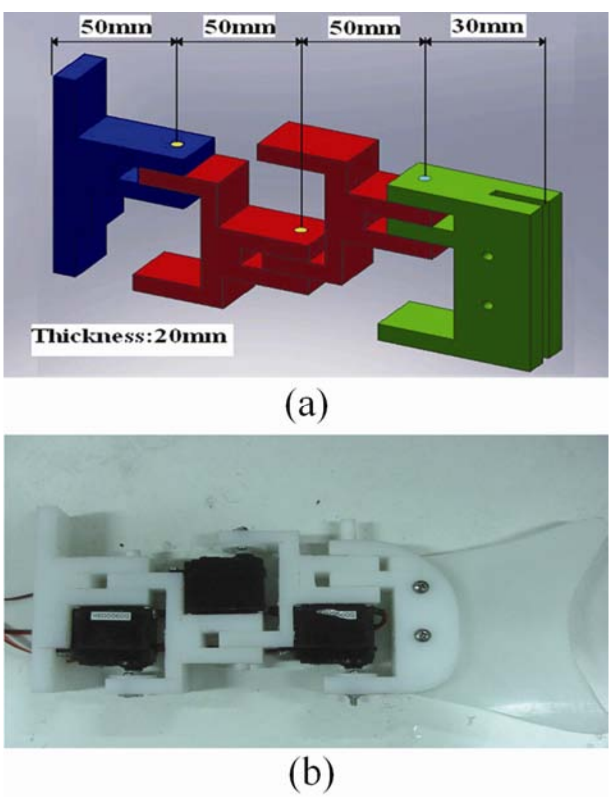

Fig. 7—(a) Combination of the Oscillatory Joints; (b) Actual Oscillatory Mechanism

Control system

The robot fish control system in the study generates signals directly through the program to control the servomotor, and this effectively simplifies the sophisticated circuit. The printed circuit board (PCB) is adopted to optimize the hardware circuit, which can effectively improve the lifespan and durability of the control circuit, reduce manmade mistakes in manufacturing, and prevent the circuit noise.

To avoid obstructions of the robot fish, a sensor must be installed. This study uses reflective infrared sensors (SHARP GP2D12) installed in the front, left, right, and below, the robot fish can detect obstructions in all four directions.

The movements of the robot fish include "advancing, turning, floating, and diving." The control center needs to output pulse width modulation (PWM) to the actuator of each joint to control the angular displacement and speed of the linkage of mechanism and receive signals from the multiple sensors to judge the status of the external environment. This increases the workload of the control chip. The overall action of the robot fish is completed in the master-slave communication mode using a number of microprocessors. Fig. 8 shows the control process.

Waterproof sealing of circuit

The general waterproof method can divided two types, one is waterproof jacket, the other is waterproof modular[11,12]. In this paper, we would adopt waterproof modular to do the waterproof sealing of the circuit. The robot fish can attain a watertight effect without using a waterproof jacket. The entire system's waterproof sealing is divided between the actuator, the control circuit and the sensor. The actuator is a regular servomotor commonly available in the market. It consists of a turning shaft, gearbox and control circuit. All parts must be waterproofed. Therefore, the servomotor's PCB and circuit contact are sealed by sealing glue. The turning shaft and gearbox on the top cover of the servomotor are filled

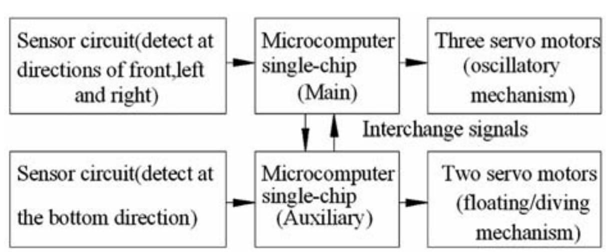

Fig. 8—Control Block Diagram

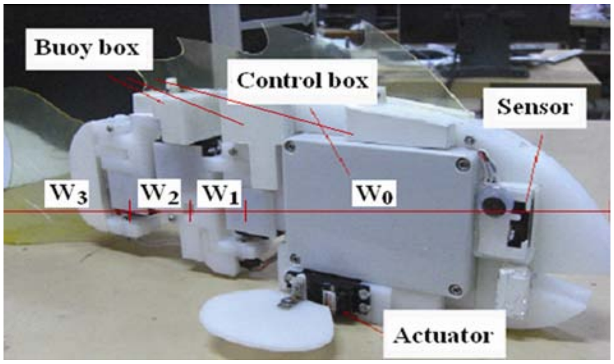

Fig. 9—Robot Fish Assembly

with gear oil to prevent water from entering when the turning shaft rotates. The non-transmission part of the entire shell is sealed by the sealing glue. The PCB of the control circuit is sealed by the sealing glue, and the entire circuit is placed into a waterproof box for double waterproofing. The robot fish is installed with a reflective infrared sensor. It is made waterproof by applying the sealing glue so that the infrared sensor functions even in water and becomes an independent watertight assembly. The sensor is placed into a transparent plastic box and is connected by the sealing glue as a stuffing. This completes the waterproof sealing of the sensor.

Fig. 9 presents the final assembly of the robot fish, total length, caudal fin length and maximum width without a pectoral fin are 480 mm, 50 mm and 80 mm, respectively. By adjusting size of buoy box, in the water, the net weight of each section with servo motor and link is $\boldsymbol{W}_0$ = 1g, $\boldsymbol{W}_1$ = 0g, $\boldsymbol{W}_2$ = 1g, and $\boldsymbol{W}_3$ = 1g, respectively. In turning motion, the microchip control the angular of oscillation of each link can be obtained, the weight distribution position is $\boldsymbol{X}_0$ = 0 cm, $\boldsymbol{X}_1$ =0 cm, $\boldsymbol{X}_2$ = 2 cm, and $\boldsymbol{X}_3$ = 8 cm, respectively. The distance $\overline{\boldsymbol{GB}}$ between the center of gravity and buoyancy of the entire fish is difficult to obtain from the experimental method: for instance, the robot fish weight can get from scales, we can place a weight on pectoral fin to obtain the torque of inclination and find the inclination angular of fish, by Eq. (7) we can get the distance $\overline{\boldsymbol{GB}}$ between the center of gravity and buoyancy of the entire fish; but in the robot fish motion, if the inclination angular of fish is to big in the motion, it is important how to deal with this problem, there is the other conception in Eq. (7), it is more bigger distance $\overline{\boldsymbol{GB}}$ to get the bigger righting moment and to prevent overturning, also, we put the buoy box at the upper structure of the robot fish, the steel plate is at the bottom of the control box, the distance $\overline{\boldsymbol{GB}}$ can be adjusted to this method in the inclination of turning motion. Using the stability method, the robot fish is very like the real fish in advancing motion and turning action, the inclination of fish is very tiny in the experimental test.

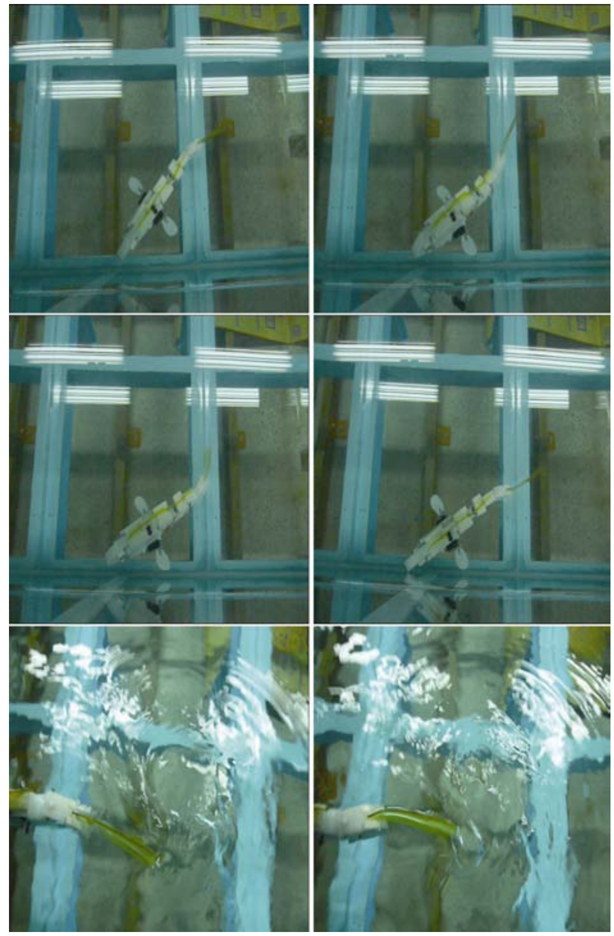

Fig. 10—Robot Fish Advances through Oscillation

Fig. 10 demonstrates its smooth swimming in water. Its tail oscillates from left to right to produce eddy currents and to propel the fish forward. On the basis of the analysis of stability, we conclude that the degree of inclination when the fish turns is reduced if the net force of the buoyancy and gravity is zero. However, it is very difficult to make such an adjustment. Hence, the distributing position of the weight is an important factor influencing the torque of inclination. In Fig. 11, the robot fish reduces the length of the weight on each joint and adjusts the distance $\overline{\boldsymbol{GB}}$; thus, its degree of inclination when turning is reduced.

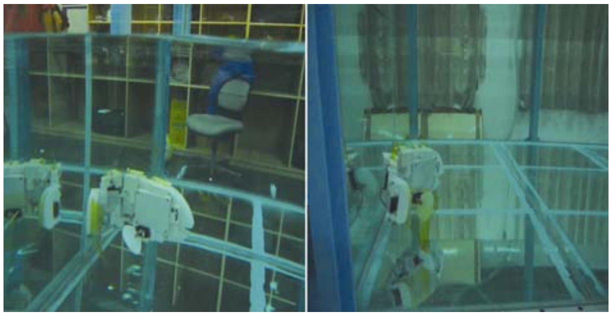

Fig. 11—Robot fish Turning

Results and Discussion

The aim of manufacturing a robot fish is to carry out the simulation effect of swimming in water like a real fish. The entire system is classified into mechanism design and control system. Through the undulation equation and by building the robot-fish linkage, the mechanism system enables the robot fish to oscillate like a real fish. Robot fish's stability when turning is the most difficult to maintain. The direction of the design is provided by discussing the stability to increase the overall stability of the robot fish and prevent it from overturning when making a turn without the change center of gravity instrument. Therefore, we would not need a high performance microprocessor to control the change center of gravity instrument; the robot fish can be finished a very lower product cost. With a double single chip, the control system can process the sophisticated actions of the actuator and the sensor. For swimming without a waterproof jacket in water, the circuit is sealed by a sealing glue that allows the actuator, control circuit, and sensor to work normally underwater.

The research effort of robot fish can be found from YouTube of video-sharing website.

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